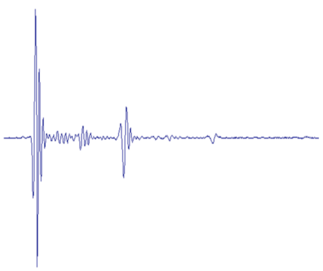
UCRL-CONF-217116
Signal and Imaging Sciences Workshop, Center for Advanced Signal and Imaging Sciences, Lawrence Livermore National Laboratory, November 17-18, 2005

SUPER-RESOLUTION ALGORITHMS FOR NONDESTRUCTIVE EVALUATION IMAGING



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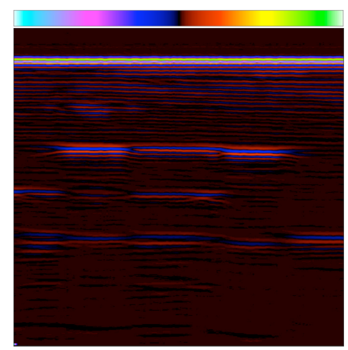

November 17-18, 2005

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Disclaimer and Auspices Statements

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Go Boilers!!!

Purdue's "All-American" Marching Band

Agenda

• **Problem Definition:**
  - **Ultrasonic NDE measurements**
  - **The spatial resolution problem**

• ***Impulse Response Estimation*** **for Enhancing Spatial Resolution**
  - **Mitigate “ringing” due to the transducer and propagation paths**

• ***Bandlimited Spectrum Extrapolation*** **for Super-Resolution**

• **Examples of Processing Results**

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Ultrasonic Pulse-Echo Signals *(A-Scans)* Are *Distorted* By the *Transducer* and the *Propagation Paths* (*“Ringing”*)

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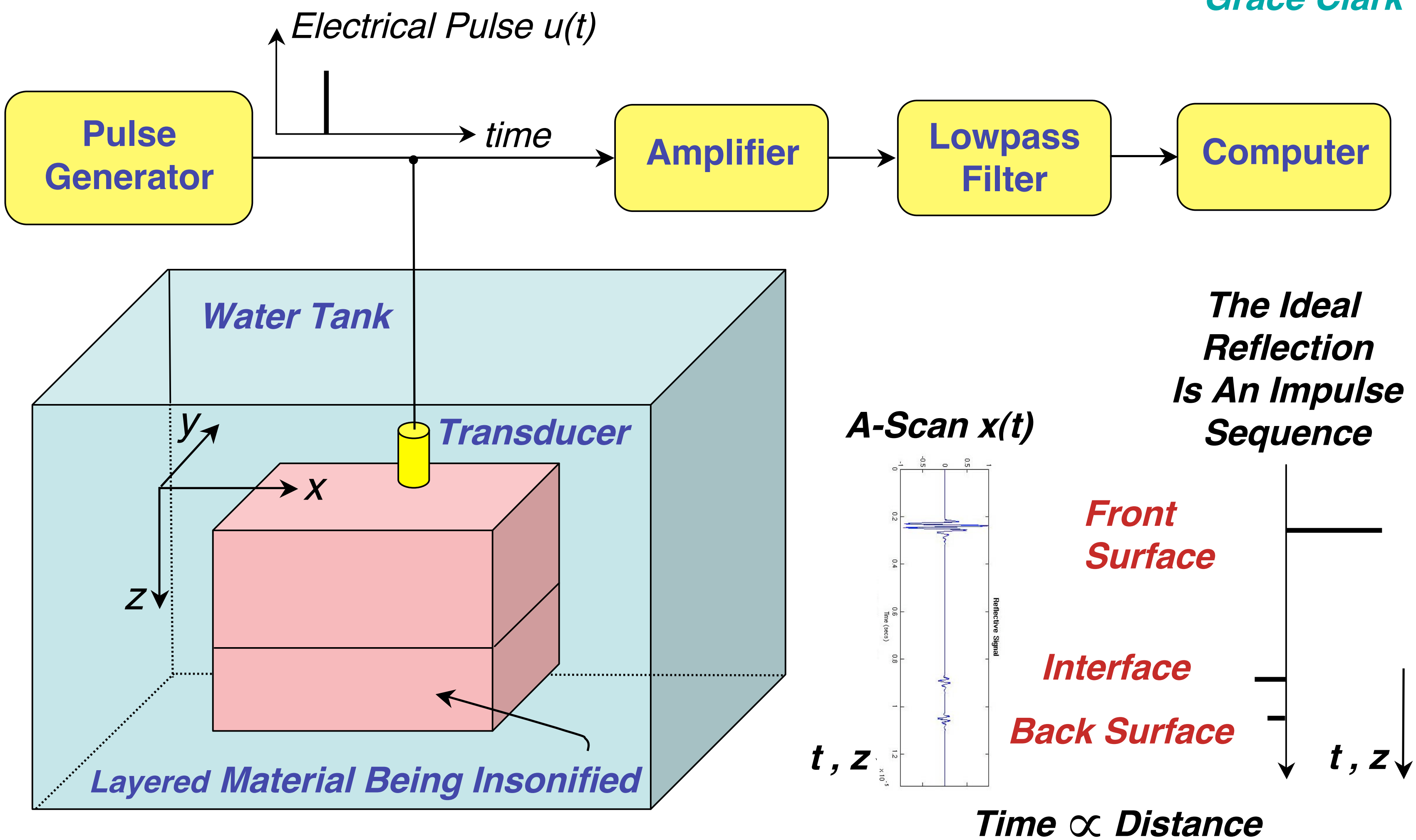
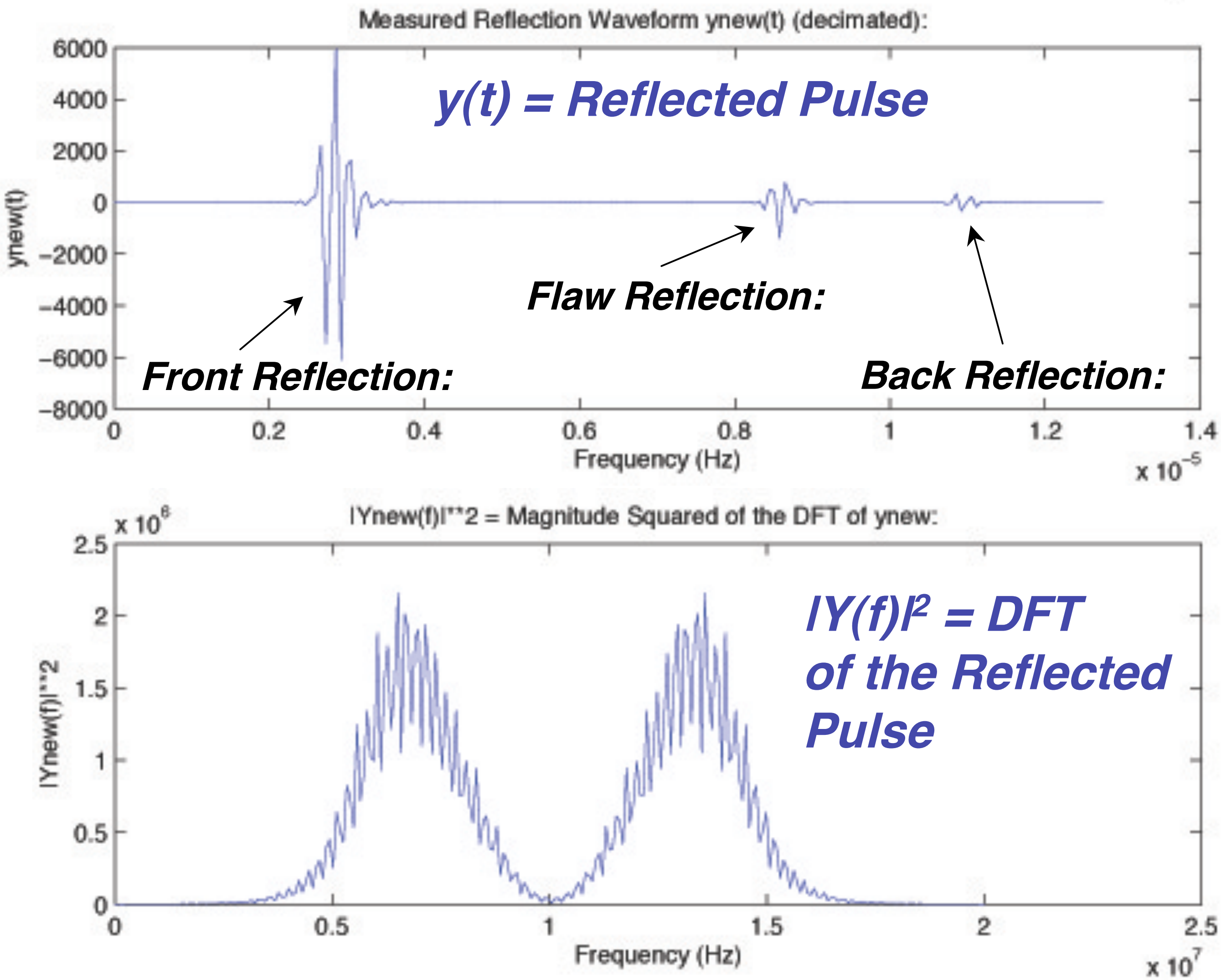


Ultrasonic Pulses Are *Bandlimited* by the Transducer ==> The Pulses *"Ring"*, *Reducing Spatial Resolution*



We Define Ultrasonic *A-, B-, and C-Scans* Used in Nondestructive Evaluation (NDE) Studies:

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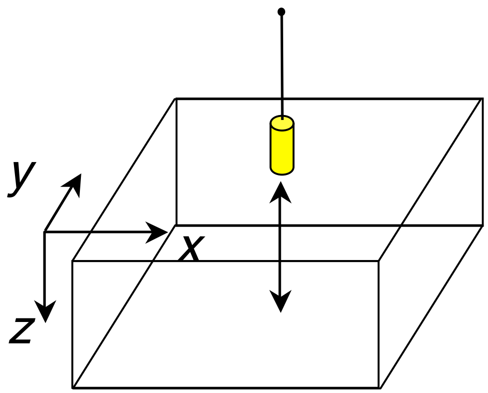
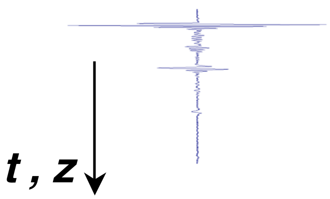
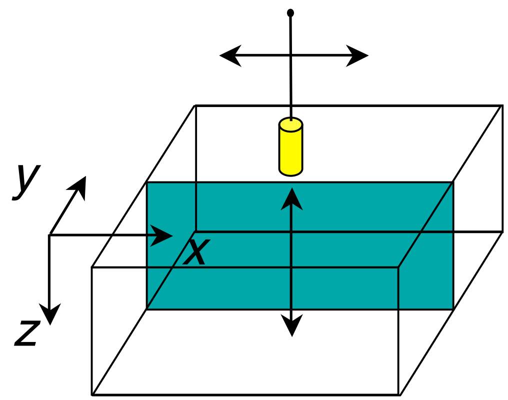


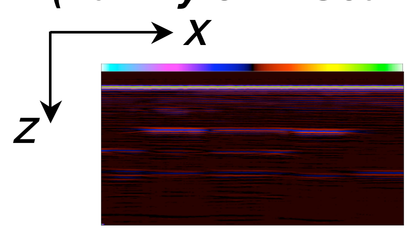
A-Scan x(t)
(A Single Waveform)



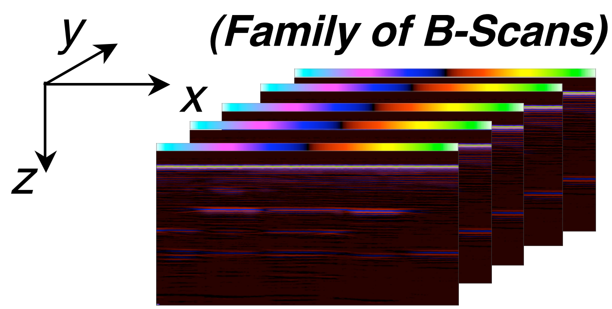
Time ∝ Distance

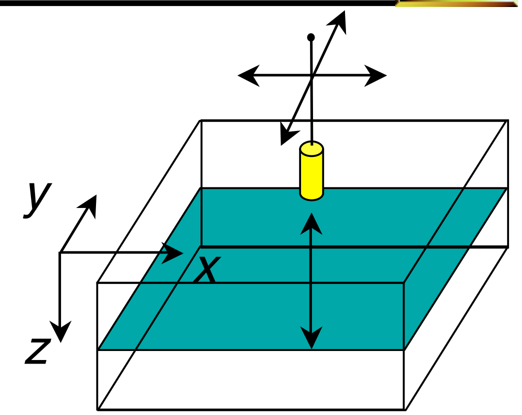


B-Scan
(Family of A-Scans)

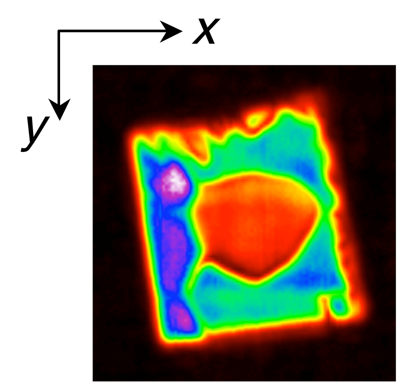


3D Volume
(Family of B-Scans)





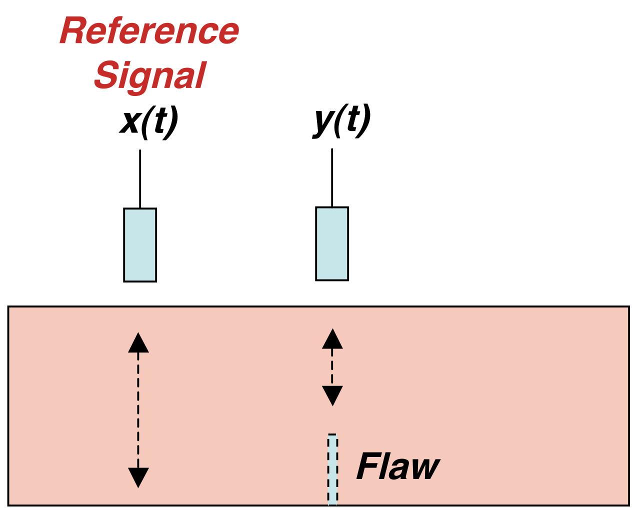
C-Scan
(Horizontal Slice At Depth z: Use A Time Gate)



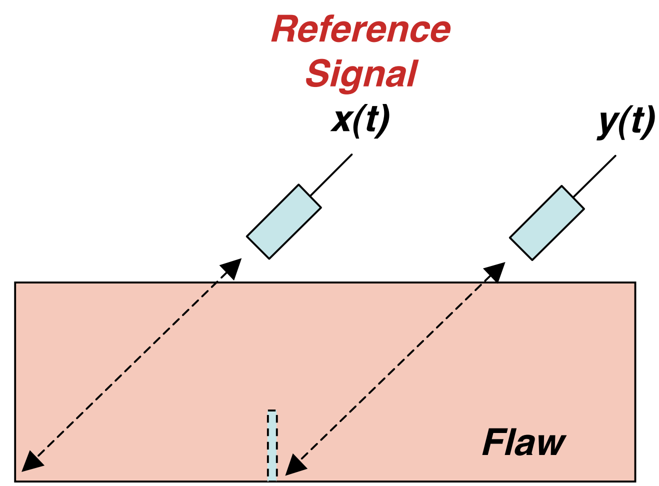
The Reference Scatterer is Chosen to Provide the Transducer / Path Response in the Absence of a Flaw

Desired properties of the reference scatterer:

- ***Reflects back most of the energy***
- ***Resembles some feature associated with the flaw environment***



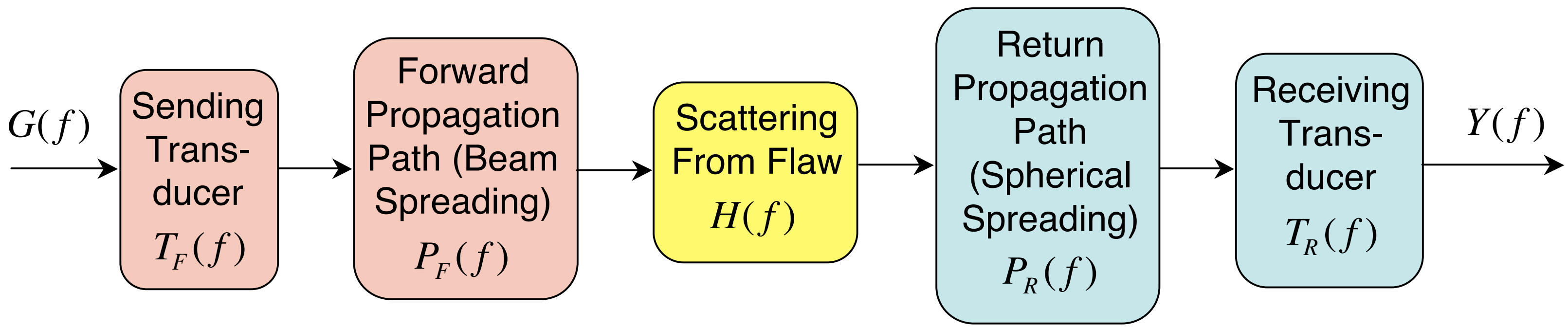
Front or Back Surface Reference



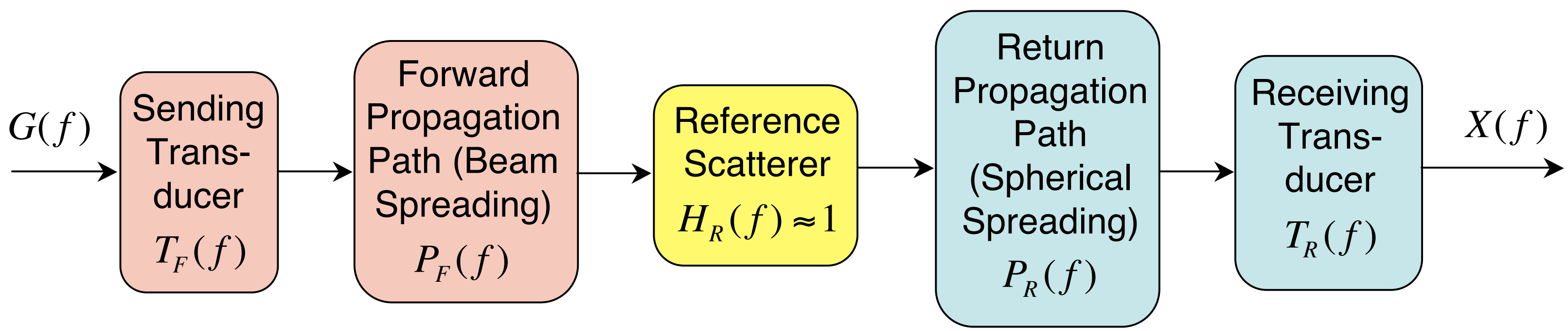
Corner Reflector Reference

We Use a Reference Scatterer to Help Remove Distortion: Conceptually, This is a *"System Identification"* Problem

Experiment to Measure the Scattered Signal $Y(f)$



Experiment to Measure the Reference Signal $X(f)$



Conceptually:

$$\frac{Y(f)}{X(f)} = \frac{\cancel{T_F(f)}\,\cancel{P_F(f)}\,H(f)\,\cancel{P_R(f)}\,\cancel{T_R(f)}}{\cancel{T_F(f)}\,\cancel{P_F(f)}\;(1)\;\cancel{P_R(f)}\,\cancel{T_R(f)}} \approx H(f) \xleftrightarrow{F^{-1}} h(t)$$

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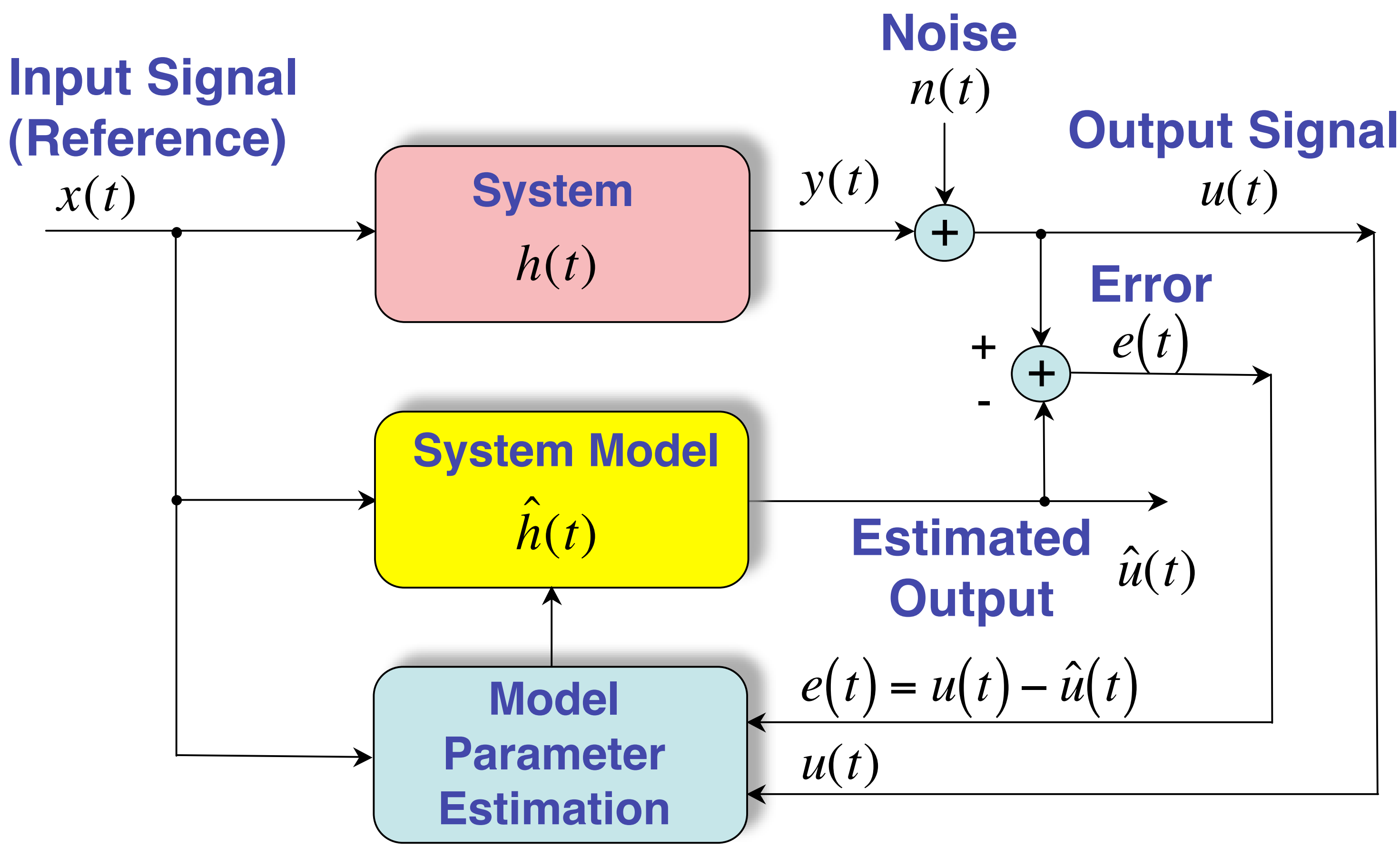
System Identification: Estimate the Impulse Response $\hat{h}(t)$

Given: $x(t)$ **and** $u(t)$ **Estimate:** $\hat{h}(t)$



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The Inverse Problem Is Very Difficult

We Must *Regularize* the Problem

- Ill-Posed
  (Infinite Number
  of possible
  solutions)
- Bandlimited
  Transducer
  Spectral
  Response
- Ill-Conditioned -
  Numerical Errors
  Due to Spectral
  Zeros

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The *System Model* and *Processing Algorithms* Are Summarized in Block Diagrams

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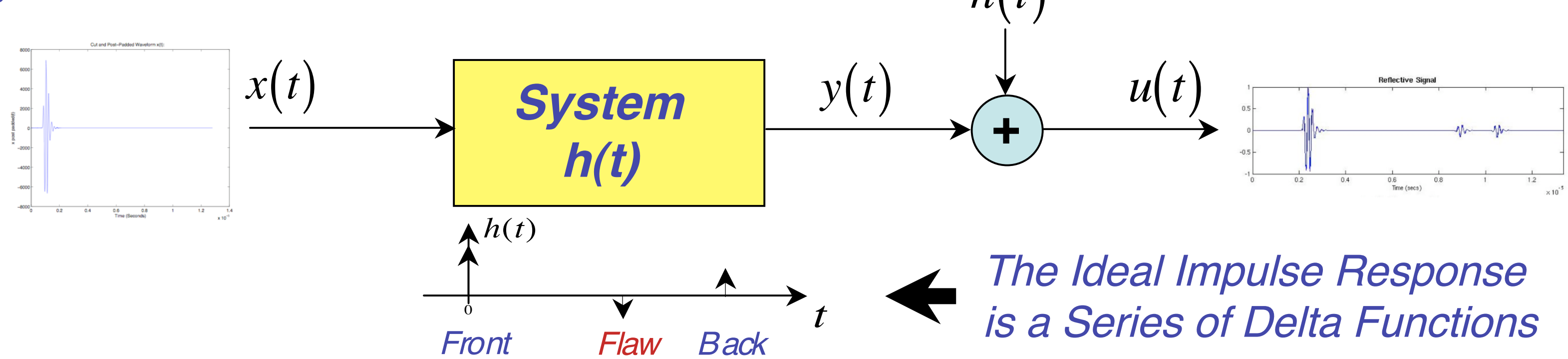
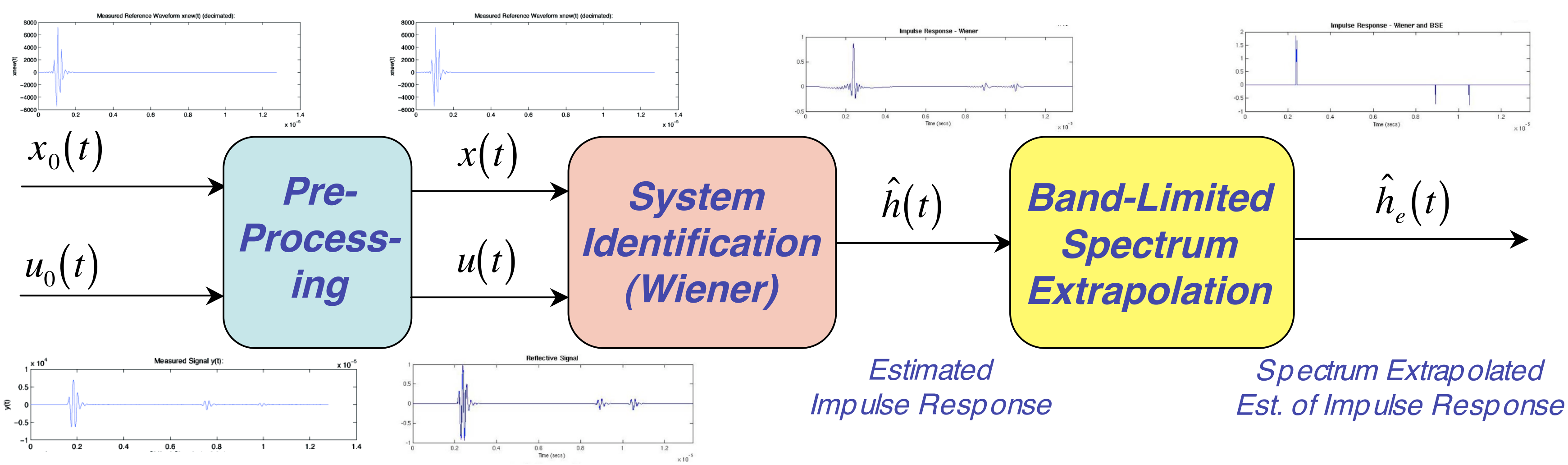
System Model



Processing Algorithms



Our Objective is to Improve Temporal Resolution by *Extrapolating Spectra*

- The transducer bandlimits our signals
  - System identification solutions are not unique
  - System identification solutions are valid only in a finite frequency interval *$[f_1, f_2]$.* They give us the optimal least squares solution, given the bandwidth of the transducer.
  - We can never obtain narrow impulses in the time domain

- We wish to extrapolate spectra beyond *$[f_1, f_2]$.*
  - This can allow us to obtain better approximations to impulses in the time domain.

- We propose to extrapolate the spectra of:

$u(t)$	*The measured pulse-echo signal*
$\hat{h}(t)$	*The estimated impulse response*

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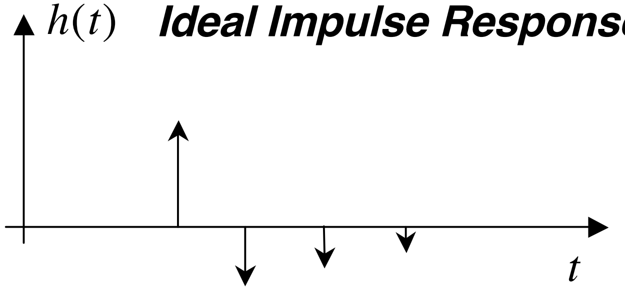
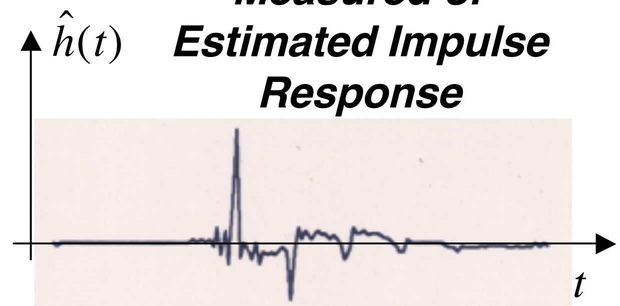
We Use *Bandlimited Spectrum Extrapolation* To Improve *Spatial Resolution*

Ideal	Measured or Estimated

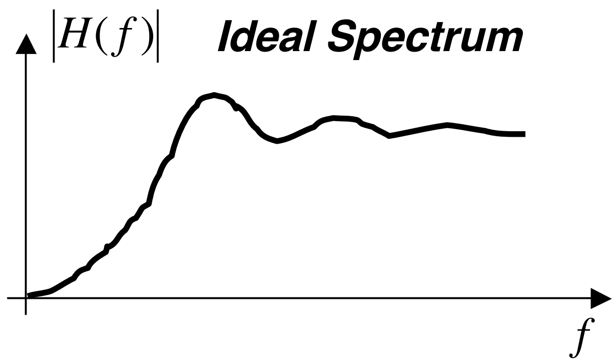
Ideal Impulse Response



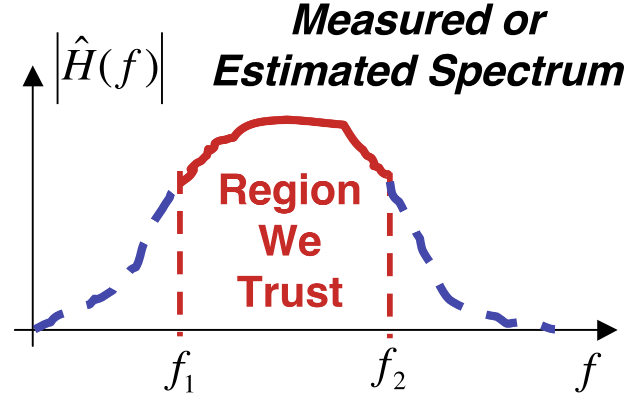
Measured or Estimated Impulse Response



Ideal Spectrum



Measured or Estimated Spectrum



$h(t)$

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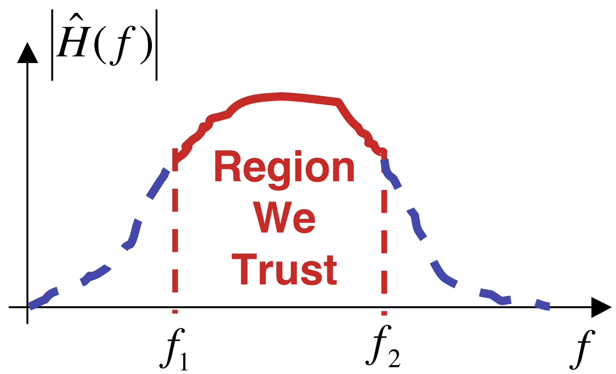
Complex Variable Theory Gives Us a Solid Theoretical Basis for Spectrum Extrapolation

- **Our temporal signals have *bounded support*:**
  - **They are transient (finite length) signals in the time domain**

- **The Fourier Transform of a signal with bounded support is *ANALYTIC* (continuous, all derivatives exist).**

- **If any analytic function in the complex plane is known exactly in an arbitrarily small (but finite) region of that plane, then the *entire function* can be found *(uniquely)* by *ANALYTIC CONTINUATION*.**



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Analytic Continuation Algorithms are Hypersensitive to Noise - *Must Regularize*

- Prior knowledge can be used as constraints to regularize the problem
- Iterative algorithms *(method of successive approximations)* are *slow*, not *unique*, but *can incorporate constraints*.
- Non-iterative algorithms are faster, but can't usually incorporate constraints.
- Often, it is not necessary to determine the inverse of the distortion operator
  - Good for nonlinear or time-varying operators

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We Use an Iterative Algorithm for *Regularized* Analytic Continuation

- Estimate the impulse response at the next iteration as a function F of the impulse response at the last iteration:

$$h_{k+1}(t) = Fh_k(\mathrm{t}), \qquad \text{for } k = 0, 1, 2, \cdots$$

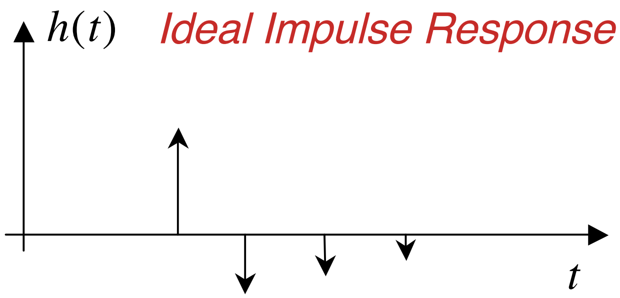
- Iterate between the time and frequency domains *(Method of Alternating Orthogonal Projections)*

- Convergence is proved using contraction mapping theorems from functional analysis

- Use an *"adaptive algorithm"* that assumes the impulse response to be a sequence of impulses - *constrain the time domain signal to be an impulse train:*

$$h(t) = \sum_i c_i \delta(t - t_i)$$

$$u(t) = \sum_i c_i x(t - t_i) + n(t)$$



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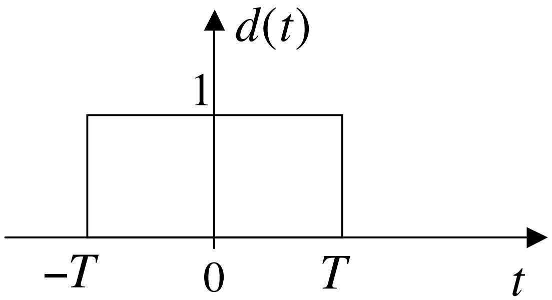
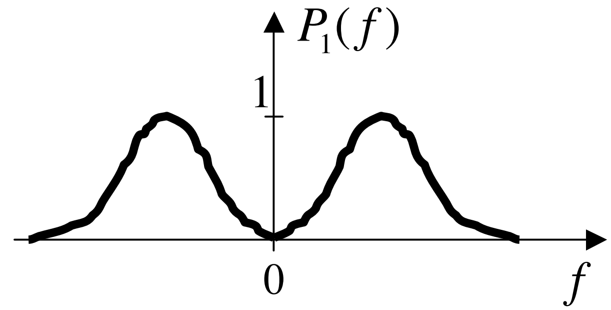
We Constrain the Temporal and Spectral *Support* Using *Projection Operators*

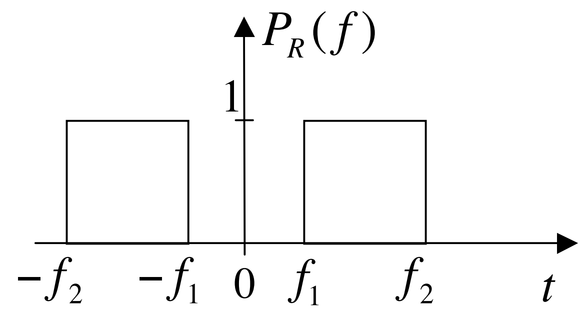
Temporal Projection Operator



Spectral Projection Operators

$$P_T(f) = \text{Envelope}\left\{ \frac{|X(f)|}{\max|X(f)|} \right\}$$





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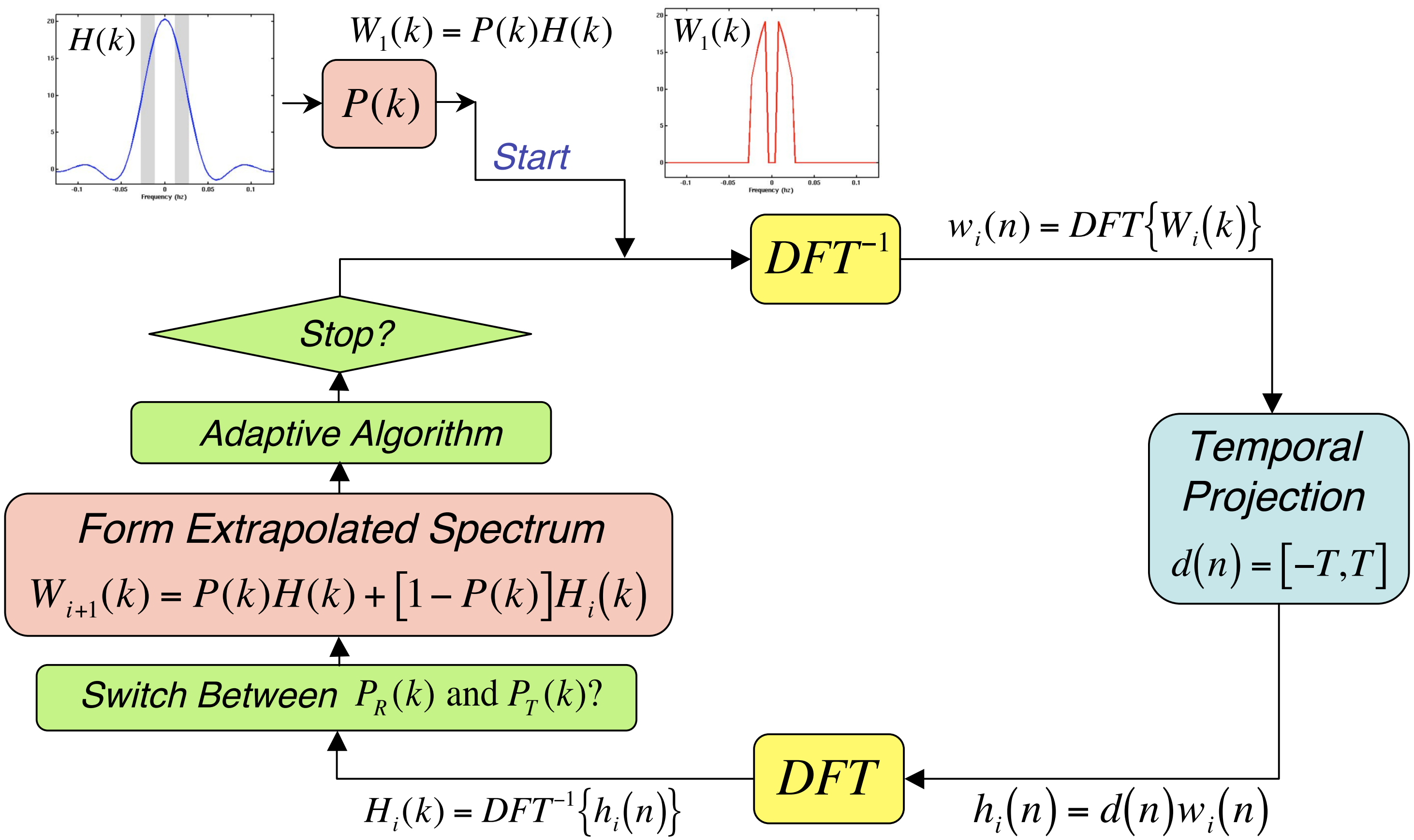
ith Iteration of the Spectrum Extrapolation Algorithm:
Alternating Orthogonal Projections, w/Adaptive Algorithm

n = Time Index = $-(N/2-1),\cdots,-2,-1,0,\ 1,\ 2,\cdots,\ N/2-1$

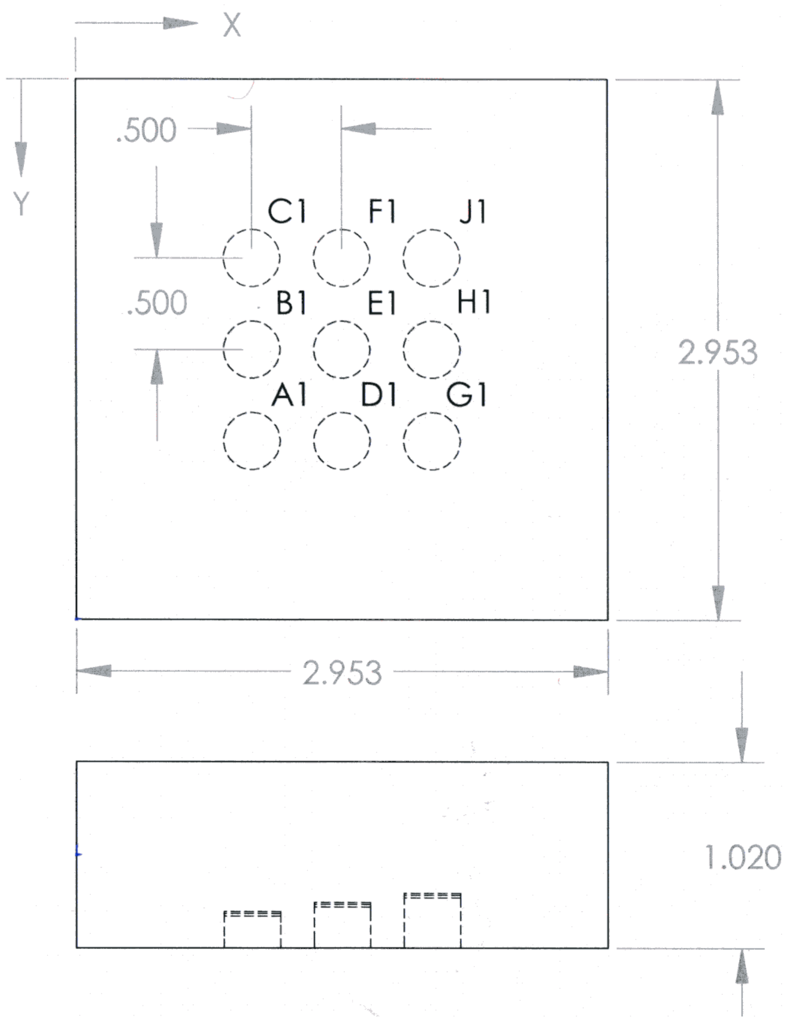
k = Frequency Index = $-(N/2-1),\cdots,-2,-1,0,\ 1,\ 2,\cdots,\ N/2-1$

$P(k)=(-k_1,-k_2)\cup(k_1,k_2)$

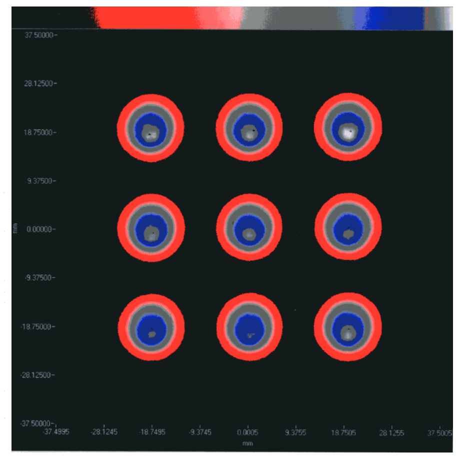
$d(n)=[-T,T]$



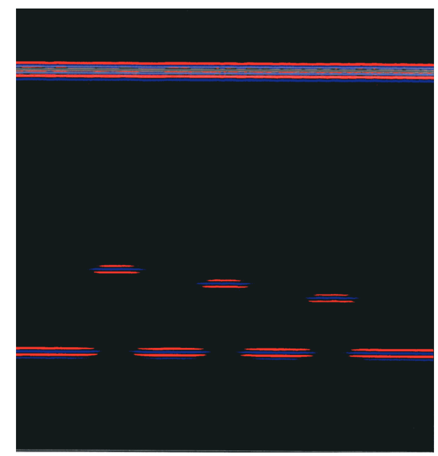
We Constructed a "Phantom" Part - *Aluminum Block* Containing *Flat-Bottom Holes*

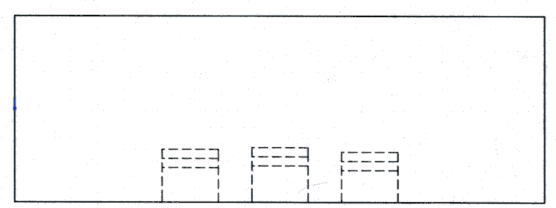


C-Scan Image (Horizontal Slice)



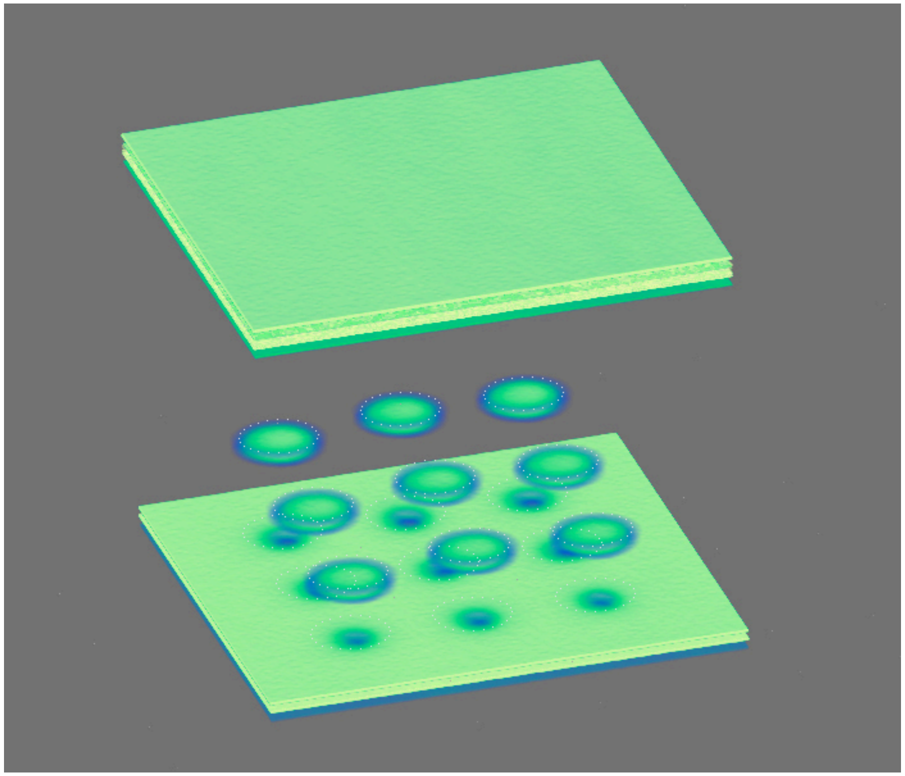
B-Scan Image (Vertical Slice)



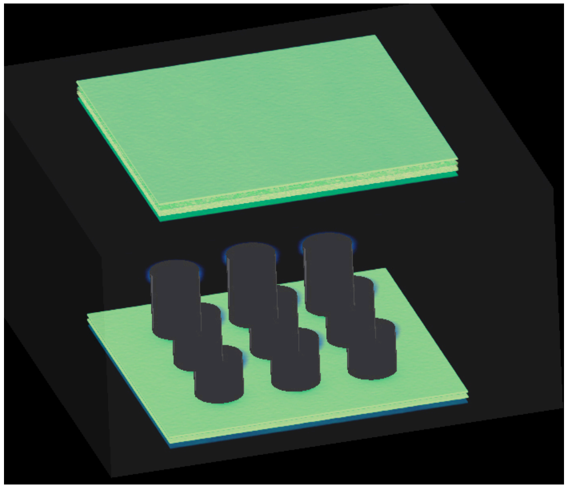


We Can Combine CAD Models With 3-D Data To Clarify Ultrasonic Evaluation Results

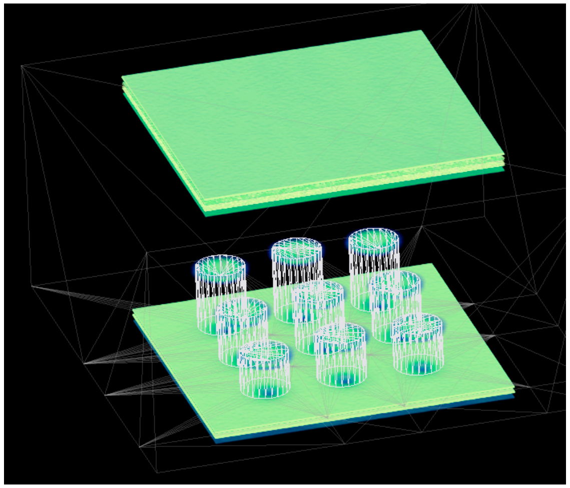
3-D Ultrasonic Data Det



3-D data and CAD Model-*Solid*



3-D data and CAD Model-*Lines*



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Processing Results Show Great *Reduction of Ringing*, and *Enhancement of Range Resolution*

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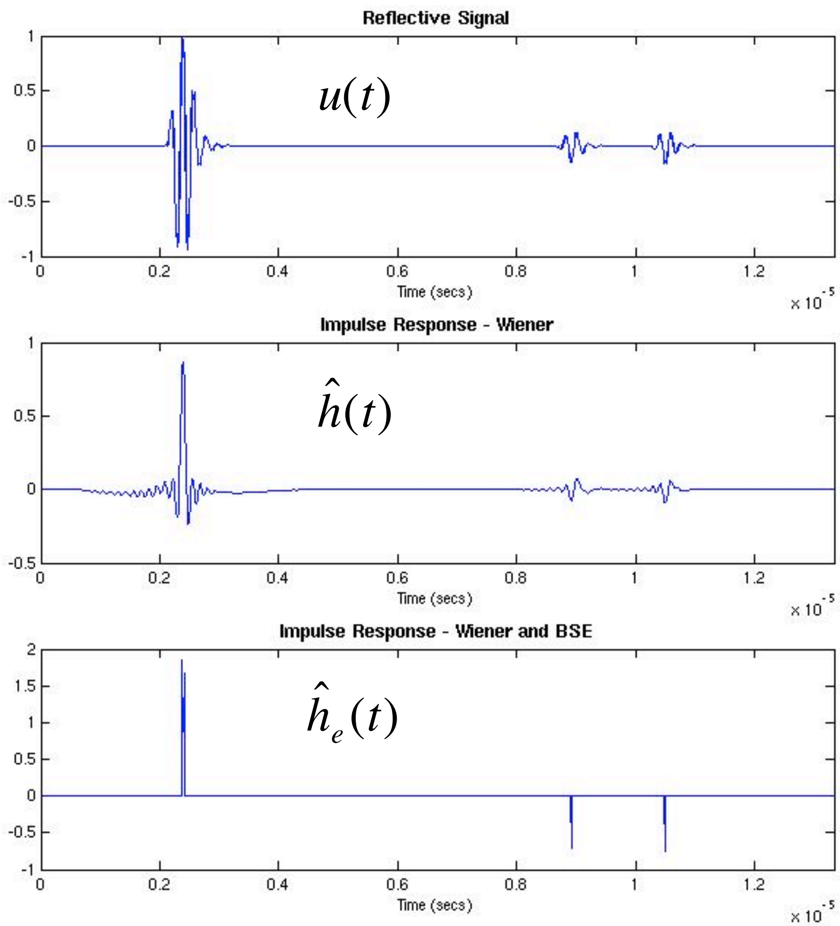
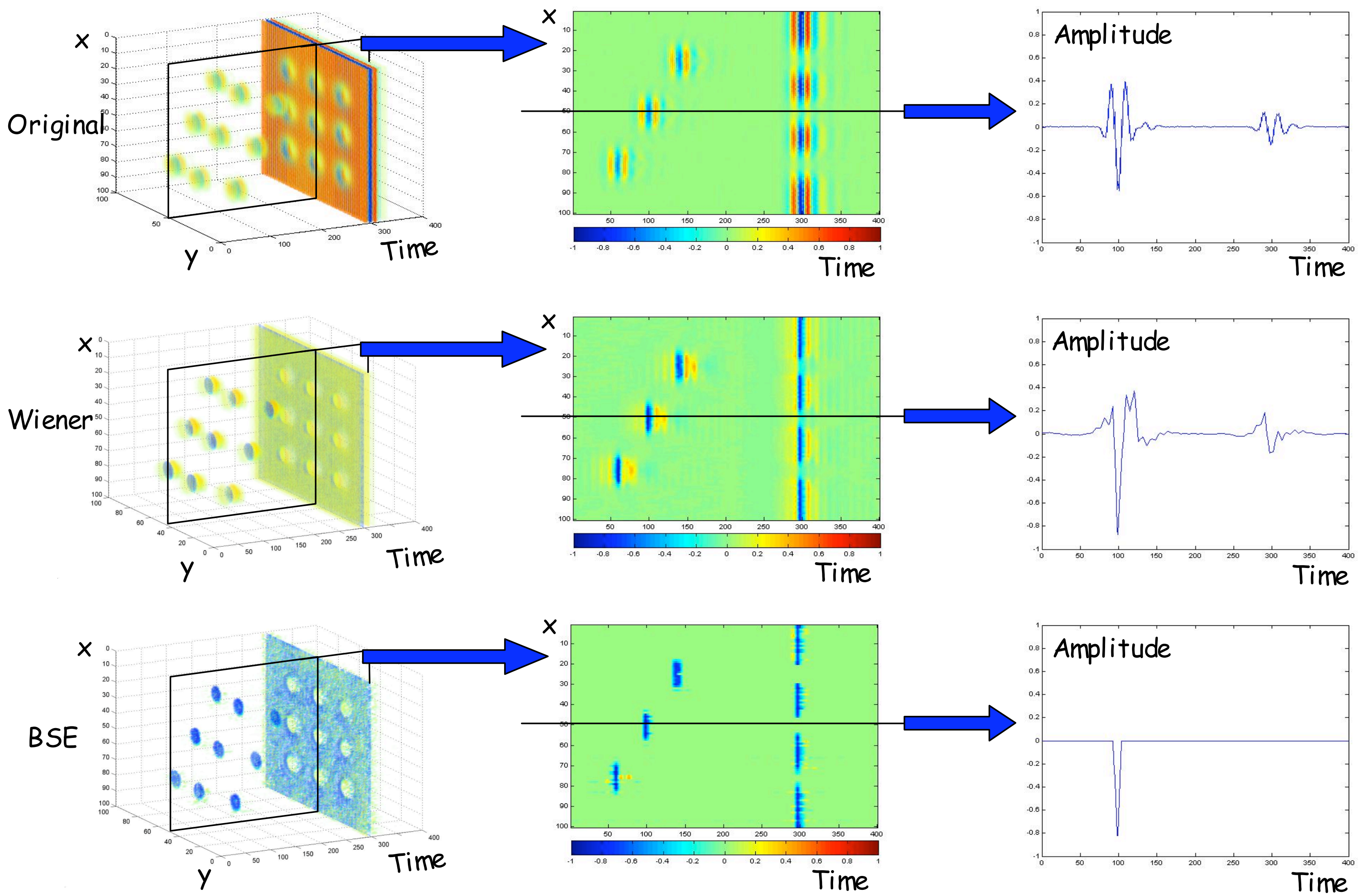


The Measured Pulse-Echo Signal Contains Transducer Ringing, Which Limits Resolution

The Estimated Impulse Response Shows the Optimal Ringing Reduction Possible, Using the Band-Limited Transducer Spectrum

The Spectrum-Extrapolated Impulse Response Estimate Allows Super-Resolution Because We Now Have a Broader Effective Signal Spectrum

System Identification and Spectrum Extrapolation Results Are *Summarized* for the *Flat-Bottom Hole Phantom* Signals



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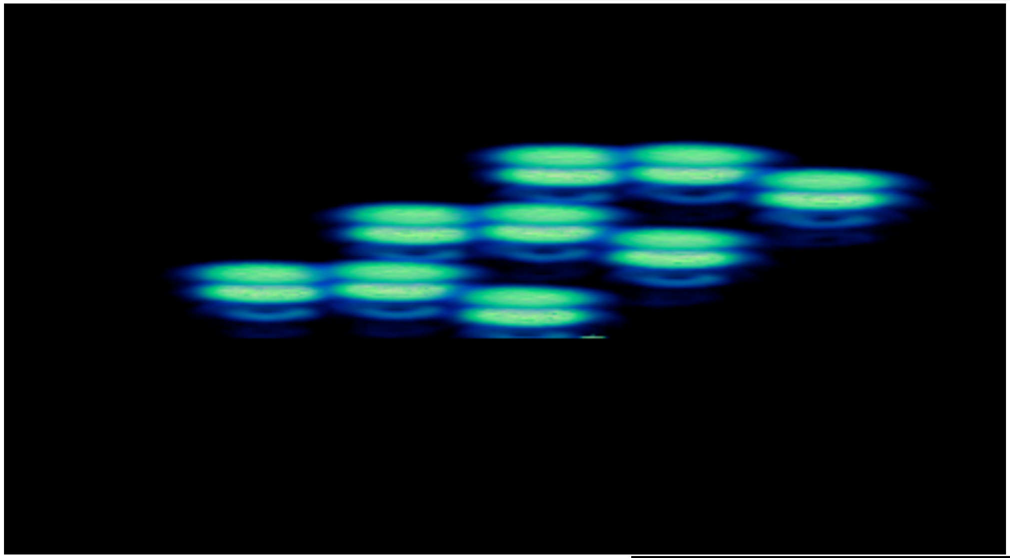
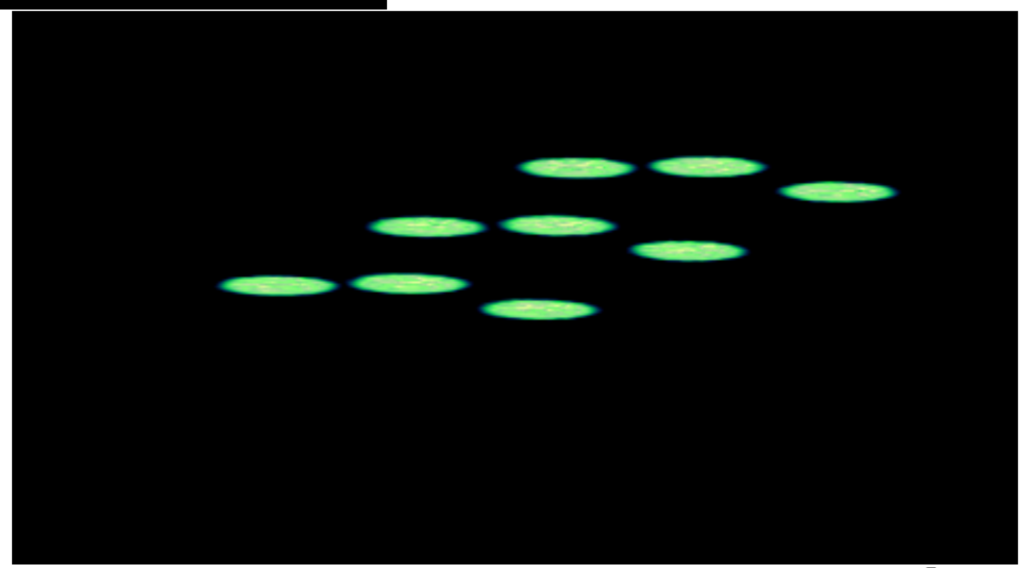
The Processed 3D Volume Shows Greatly-Enhanced Spatial Resolution *(System ID Only)*



Raw 3D Volume

Processed 3D Volume (System ID Only)



Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths

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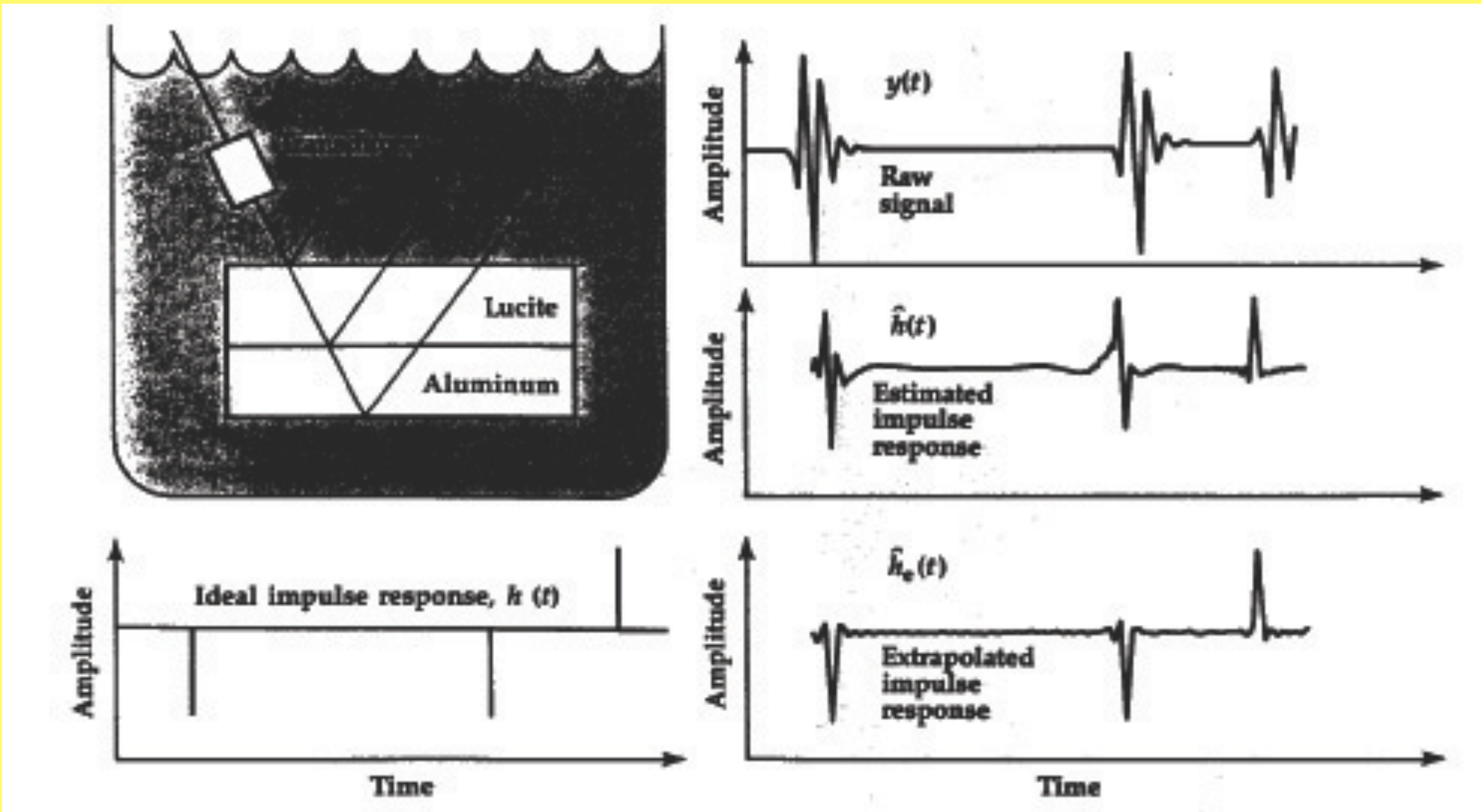

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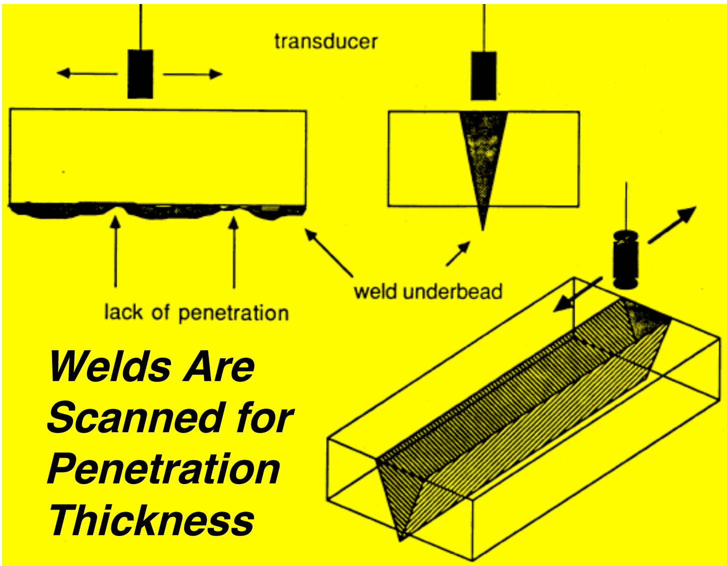
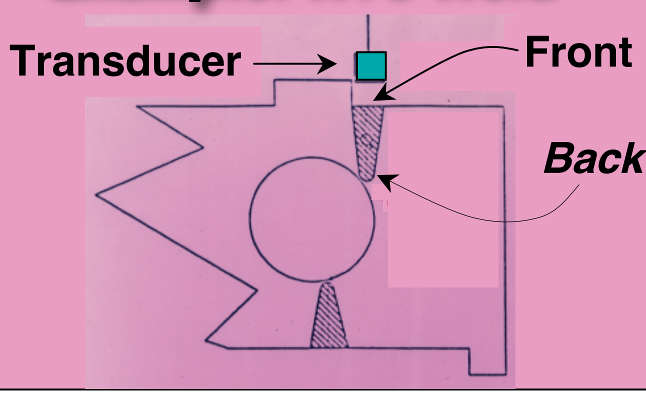
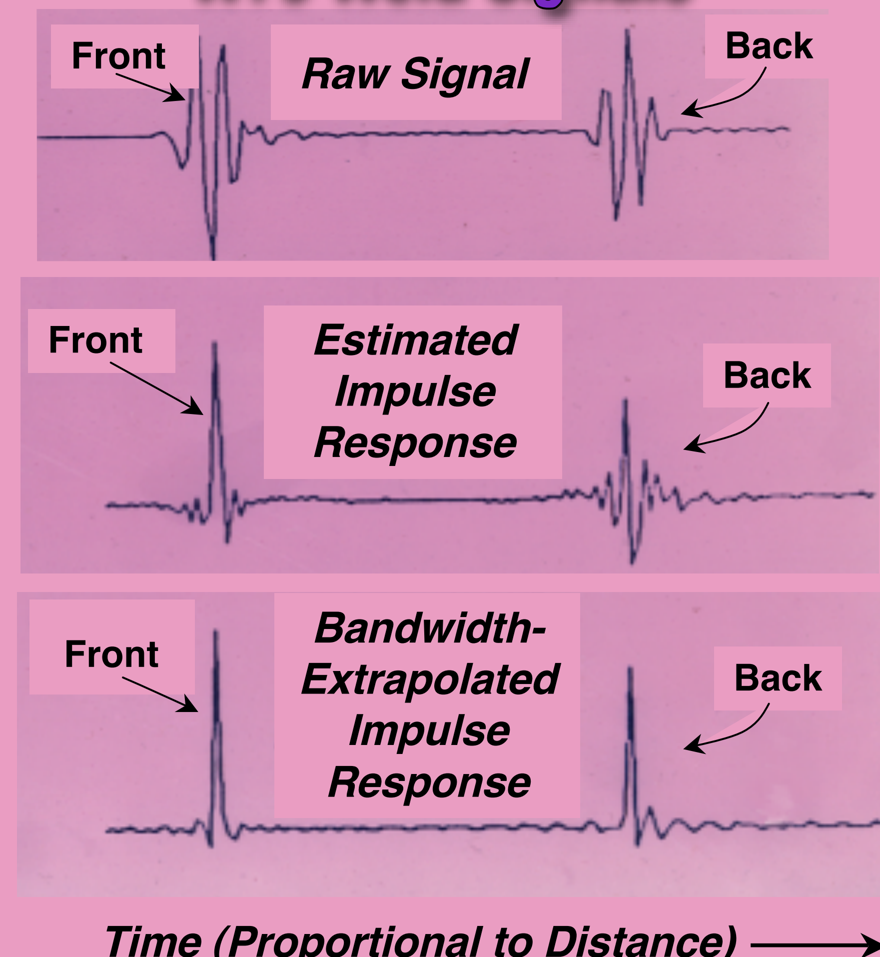
Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths



Example: W79 Weld



W79 Weld Signals



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